REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
15 June 95

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
"Hierarchical Production Planning and Scheduling in the Apparel Industry"

5. FUNDING NUMBERS
DLA 900-87-D-0017
Delivery order 00

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Logistics Agency
Room 4B195 Cameron Stat.
Alexandris, VA 22304-6100

Defense Personnel Supply Ctr
P.O. Box 8419
Philadelphia, PA 19101-8419

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE
UNLIMITED

13. ABSTRACT (Maximum 200 words)

The independent nature of current scheduling methodology can lead to conflict and inefficiences. Short term production schedules may not be consistent with daily operational capabilities. Thus, establishing a formal link between long-term, short-term, and daily planning procedures would ensure consistency and can result in more efficient operations. Hierarchical production planning and scheduling os proposed to formally link long-term, short term, and daily planning tasks.

14. SUBJECT TERMS

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	unclassified

Hierarchical Production Planning and Scheduling in the Apparel Industry

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INTRODUCTION

Apparel manufacturers constantly struggle with production-related problems such as large inventory quantities, long lead times, and high levels of work-in-process. The resolution of such problems represents a significant portion of the industry-wide emphasis on *quick response* — an apparel initiative aimed to meet market demand in a timely, efficient manner [10]. Although quick response is a broad initiative spanning many facets of the apparel industry, production planning and scheduling techniques remain an integral part of its success.

Current production planning and scheduling tasks address long-term capacity planning, short-term production planning, and daily machine scheduling. Most often these planning and scheduling activities are carried out manually with no formal link between tasks. Long-term planning is typically implemented by high level management incorporating aggregate demand forecasts over an extended time horizon. On the other hand, short-term planning is done by a production scheduler at a lower, more detailed level over a shorter time horizon. Daily planning addresses operational machine scheduling and is typically done by a shop floor supervisor.

The independent nature of current scheduling methodology can lead to conflicts and inefficiencies. Short-term production schedules may not be consistent with daily operational capabilities. This can increase work-in-process, lead times, and inventory levels. Thus, establishing a formal link between long-term, short-term, and daily planning procedures would ensure consistency and can result in more efficient operations.

A three-tiered *hierarchical production planning and scheduling model* is proposed to formally link long-term, short-term, and daily planning tasks. The first level model addresses the long-term aspect of production planning. It determines monthly production quantities for stock items as well as overtime and subcontracting levels to minimize total production and inventory costs over a period of 3 to 18 months. In addition, the first level model seeks the best monthly plant layouts to balance and smooth production. The second level model focuses on the assignment of production to manufacturing lines and/or modular units to balance production loads among these lines and modulars as well as minimize unmet demand. This short-term planning model operates over a period of 4 to 6 weeks. The third level model seeks the appropriate job orderings through required operations to minimize unmet demand over a period of one week.

BASIC METHODOLOGY

Most production planning and scheduling models focus on only long-term, short-term, or daily planning. However, a few models provide explicit means by which to link these tasks. Early attempts to link long-term and short-term planning take what Graves regards as the *monolithic approach* [9] in which both the long-term planning problem and the short-term scheduling problem are combined to yield one very large problem [8, 12, 13]. In practice, the extreme size of these models prevents their computational implementation.

In contrast, hierarchical models [3, 4, 5, 6, 7, 11] take a modular approach to linking long-term and short-term planning. In hierarchical models, decisions made at one level impose constraints within which lower level, more detailed decisions are made. Subproblems are optimized at each level in the hierarchy. Thus, the model does not attempt to optimize a single representative model as does the monolithic approach and offers at best optimal solutions to the individual subproblems at each level.

The proposed hierarchical model encompasses an apparel production planning system that integrates all aspects of the planning process from long-term planning to detailed daily scheduling. No operational inconsistencies arise since decisions must be made within limitations imposed at higher levels. The model includes a feedback mechanism whereby deviations from the model-generated plans forced by actual events are incorporated into appropriate parameters at higher levels in the model structure. In effect, the model is periodically adjusted to reflect actual operations with these adjustments influencing future decisions. Hence, the hierarchical approach provides for a consistent and dynamic planning model.

A description of a hierarchical production planning and scheduling model for apparel manufacturing follows. First, some specifics pertaining to apparel production are discussed. Next, an overview of the dynamics of the three-tiered model is given. Finally, model implementation is discussed followed by a detailed description of each level in the model hierarchy.

PRODUCTION PLANNING IN THE APPAREL INDUSTRY

Types of Apparel Manufacturers

The nature of apparel manufacturing complicates the production planning and scheduling process. Apparel companies can be classified into two types—style shops and basic apparel manufacturers. Style shops change product lines seasonally. Demand forecasting is difficult. Since excess inventory invariably leads to losses, style shops may attempt to gain insight as to style preferences through a small number of early showings. This consumer information is used to fine tune earlier demand forecasts and determine production quantities for the season's first production or *stock run*. Since these companies thrive on change, most manufacturers have a mixture of sewing equipment composed largely of multipurpose generic sewing machines with a smaller amount of highly specialized equipment. Long-term planning usually extends over a period of 3 to 6 months. The primary purpose of such long-term scheduling is to determine production times and quantities for stock run production, decide overall capacity allocation among regular time, overtime, and subcontracting, as well as establish monthly plant layouts.

Basic apparel companies such as dress shirt manufacturers change product lines less frequently. For these companies, historical data provide more accurate means by which to predict future demand. To lessen the risk of stockouts and the associated decrease in customer service, most companies maintain a finished goods inventory. Also, due to infrequent style changes, most basic apparel manufacturers employ a relatively large proportion of highly specialized equipment as compared to multipurpose generic sewing machines. Long-term planning usually extends over a period of 6 to 18 months. The primary purpose of such long-term scheduling is to determine overall capacity allocation among regular time, overtime, and subcontracting and to establish monthly plant layouts as well as production times and quantities for all inventoried items.

Scheduling for Basic Apparel Manufacturers versus Style Shops

The primary difference in scheduling efforts required of a basic apparel manufacturer versus a style shop lies in the long-term aspect. The long-term time horizon for a style shop is much shorter than for a basic manufacturer. Long-term data inputs differ as well. Demand predictions for a basic apparel manufacturer represent a combination of known orders and fairly accurate, detailed end item demand forecasts. End item stock run quantities and estimates of aggregate product demand along with periodic product reorders combine to form demand forecasts for style shops.

Basic apparel manufacturers and style shops share common short-term and daily scheduling activities. The main difficulty with these scheduling efforts is the necessity to process an overwhelming amount of information. Short-term scheduling requires the integration of long-term production plans and weekly orders and reorders to describe short-term demand. Such integration is a formidable task. The job is particularly difficult for a style shop as the planner must adhere to the most recently developed plan for long-term inventory item production while frequently incorporating new orders.

Once short-term demand is determined, a planner must then produce a four to six week schedule that assigns production to specific modular units and/or production lines according to their individual capacities. Most often, production is loaded based simply on direct labor hours. This practice leads to inefficiencies in daily scheduling efforts. By loading production based on direct labor hours without regard to the specific manufacturing operations and equipment required for each end item or style, some individual operations or modular units are likely to be overloaded while other production units are under utilized.

The results of such practices are costly. After weeks of such scheduling with no changes in personnel or equipment, the cumulative effects among production units are long lead times and large work-in-process inventories. It is no surprise that many apparel manufacturers quote six week lead times from cutting to shipping and carry six or seven weeks of work-in-process inventory. Alternatively, ad hoc manual scheduling techniques that often involve frequent changes in both personnel and equipment, prove to be equally costly. Frequent changes in equipment and personnel lead to declines in quality, efficiency, and throughput.

The scope of the information required to properly address these scheduling issues is often beyond human or manual processing capabilities. The capacities of production lines and/or modular units may change as the critical or bottleneck operation changes. Bottleneck operations can depend on the particular styles being produced. For example, a pocket welting operation may create a bottleneck for one particular style while a zipper set operation creates a bottleneck for another style. As mentioned previously, a scheduler must not only integrate long-term plans with current orders and reorders to generate short-term demand but also know direct labor hours associated with each style as well as all operations required for each style and the corresponding bottleneck operations and capacities. Even assuming this information is available, it is extremely difficult for an individual to manually track, interpret, and process such a large quantity of information. A formal production planning and scheduling model is needed to process these data and provide the necessary links to yield an integrated, consistent, dynamic model.

AN OVERVIEW OF THE HIERARCHICAL MODEL

Due to the size and scope of the production planning and scheduling problem, a modular approach is taken. A formal hierarchical planning model is designed which operates over a rolling time horizon. Three decision levels are considered and modeled as distinct, but interconnected, subproblems.

The first level model, the long-term planning subproblem, establishes periodic plant layouts and focuses on the allocation of regular, overtime, and subcontracting capacity to end item production on a long-term basis to minimize total cost. It sets desired stock item production quantities and inventory levels for basic apparel manufacturers over a time horizon of 12–18 months. Alternatively, the long-term planning subproblem can determine first stock-run production quantities for style shops over a full seasonal cycle of three to six months. The second level model, the short-term planning subproblem, combines first stock-run or stock item demand with special or known orders and assigns production to manufacturing facilities to balance the production among lines and/or modular units and minimize unmet demand over a four to six week time horizon. The third level subproblem, the daily scheduling subproblem, sequences jobs through required operations to minimize unmet demand. The corresponding time horizon is one week.

Solutions to each of the subproblems are obtained only for the first period in their respective time horizons. After the first period, more accurate information becomes available through actual orders received or possibly through improved demand forecasts. Actual capacity and inventory levels are compared with model predictions and adjustments to associated model parameters are made. Each subproblem is then solved for the next period incorporating the updated information and the entire process is repeated. A diagram of the planning system is given in Figure 1.

Model Formulation And Solution

Each of the three subproblems in the hierarchy is formulated using mathematical programming techniques. The basic methodology employed for each subproblem is linear programming. Linear programming is an iterative mathematical procedure used to attain a particular goal (cost minimization) subject to constraints on the availability of resources (personnel, equipment, raw materials) [2]. A real world problem is translated into a mathematical model consisting of a linear objective function and linear constraints. Decision quantities are incorporated as decision variables. A special linear program called a mixed integer program is used to implement the short-term planning subproblem. A mixed integer program is a linear program in which some decision variables are limited to integer (discrete) values.

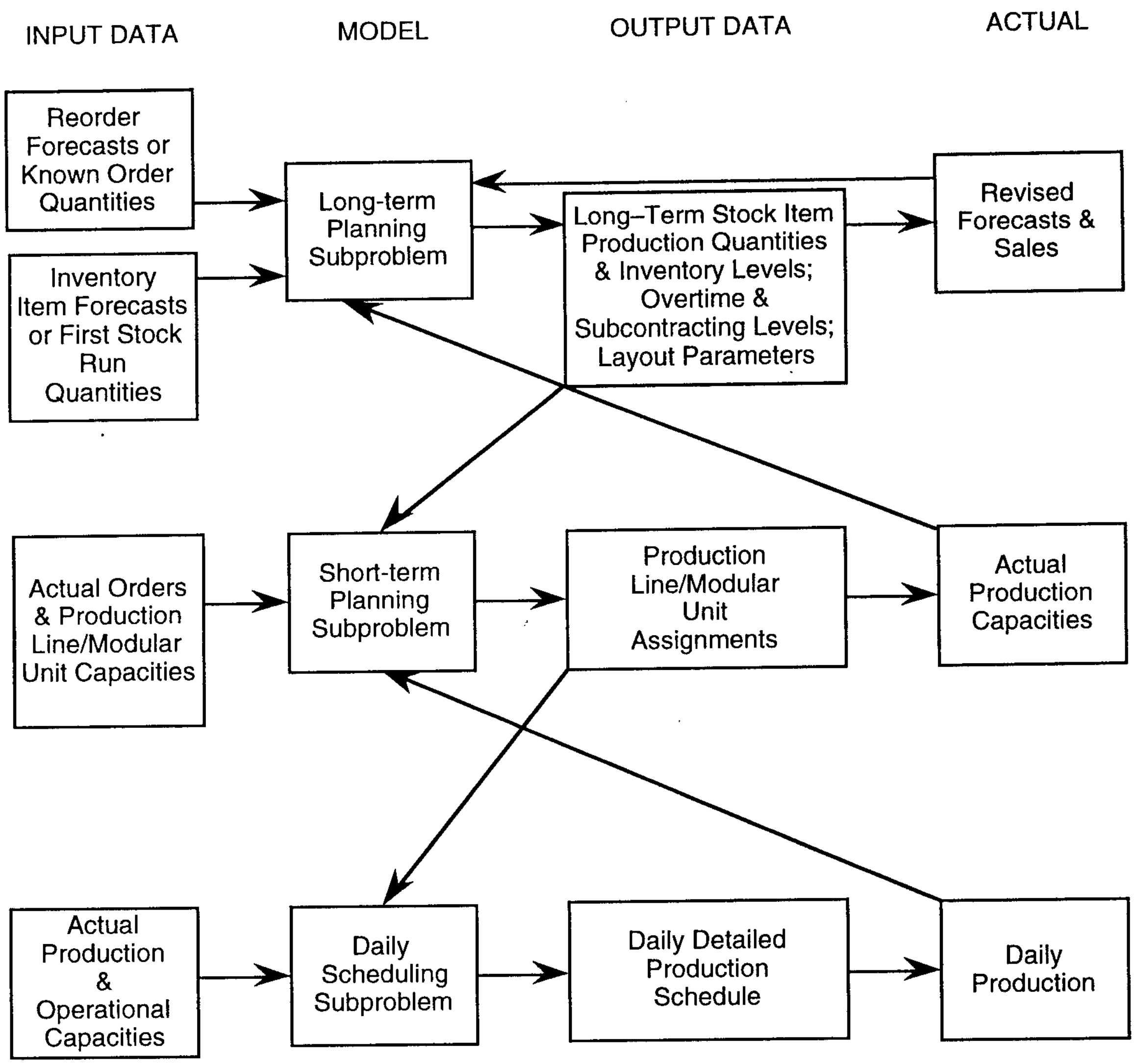

Figure 1. The Hierarchical Planning System

Long-Term Planning Subproblem

The first level subproblem, the long-term planning subproblem, establishes periodic plant layouts and focuses on the allocation of regular, overtime, and subcontracting capacities to the production of inventory items or first stock-run goods as well as other anticipated production requirements to satisfy demand and minimize total cost. Product demand for a basic apparel manufacturer differs from that for a style shop. Estimates for long-term demand for basic apparel manufacturers are based on fairly accurate monthly end item demand forecasts derived from historical data. These are combined with actual order quantities to produce overall demand values. Style shop long-term demand is composed of a combination of specific end item demand quantities and due dates for either the season's first stock-run or subsequent reorders as well as reorder forecasts. Reorder forecasts are typically sketchy and often do not appear in end item demand format. Instead forecast reorder demand is often generated in aggregate for large groups of similar styles.

Given the model inputs, a linear program determines the quantity, time, and plant layout (or means of production) to meet demand and minimize finished goods holding costs as well as regular, overtime, and subcontracting costs within corresponding capacities. The model employs a 3–18 month planning horizon (depending on the needs and type of manufacturer), but only the results from the first month are incorporated as constraints in the second level model. (The second level model will be resolved for later months as those times become imminent.) At the end of the month, model parameters are updated and the inventory subproblem is reoptimized. The complete linear programming formulation for the long-term subproblem appears in the appendix.

An initial implementation of this long-term model was tested at Tanner Companies, Inc., Rutherfordton, NC. Testing a long-term model requires significant effort in labor, time, and data requirements. To perform a cost and performance comparison based on historical data would require 12–18 months of past data. Historical data in such a format was not available for performance testing at Tanner. However, a group of individuals collected a small set of aggregate data for use in testing the long-term model. The information collected represented monthly data estimates for a portion of the business over a six month period. The breadth and size of the data set were somewhat smaller than for the full long-term model. The model was tested using this limited set of data and Tanner personnel were pleased with the results. However, there were no historical figures with which to compare performance and cost of the resulting schedule. The model remains at Tanner for their use. However, to our knowledge, Tanner has not yet been able to dedicate sufficient labor resources to continue model use or testing (March 1995).

Short-Term Planning Subproblem

The second level model, the short-term planning subproblem, integrates results from the long-term planning model with the production of special or reorder items to attain product to line and modular assignments. As demand quantities and due dates for order and reorder items are established, this information is combined with the production of inventory items and first stock-run quantities specified by the long-term planning model. Given the short-term demand, a mixed integer linear programming model (MIP) can be used to determine the product to manufacturing line and modular unit assignments. Production assignments are made to balance production among lines and modulars and to minimize unmet demand subject to production capacities corresponding to the level one plant layout specifications. Only results from the first week of the 4–6 week planning horizon are included in the third level scheduling model. At the end of each week, model parameters are updated and the short-term subproblem is reoptimized for the next 4–6 week horizon.

A complete listing of the mixed integer linear programming formulation is in the appendix. When this model was implemented at Tanner, it was tailored to their specific production environment. Details of these changes are listed in the appendix as well.

At Tanner, the size of the second level mixed integer model precluded finding its exact solution using readily available software. Thus, a heuristic scheduling procedure based on a simple sort routine was developed in conjunction with the MIP model to ensure comparable performance results. Since the first level model was not in place, an effort was made to incorporate finished goods inventories at this intermediate level in the hierarchy in both the MIP (as described in the appendix) and heuristic models. To minimize inventory holding costs, the heuristic loads jobs into appropriate departments by week in sorted order based on earliest due date. To reduce production line imbalances, it makes all such production assignments within departmental production capacities as established by management on a weekly basis. To achieve an appropriate balance between production shortfall and finished goods inventories, management was permitted to alter weekly departmental production capacities to establish a schedule with the desired trade-offs.

More specifically, the short-term scheduling heuristic (Figure 2) first sorts jobs based on selected attributes as follows: (1) job priority in ascending order, (2) due date in ascending order, (3) size of job in descending order, and (4) date job entered the system in ascending order. (The job priority is a vehicle by which the scheduler may expedite a given job. As hoped, it was seldom necessary to use the job priority attribute to expedite a job.) Next, jobs are loaded in sorted order into appropriate departments based on management-established weekly production availability to minimize production shortfall through a balance among production lines and modular units that serves to directly reduce work in progress (WIP). The secondary sort attribute tends to minimize finished goods inventories by loading jobs based on earliest due date.

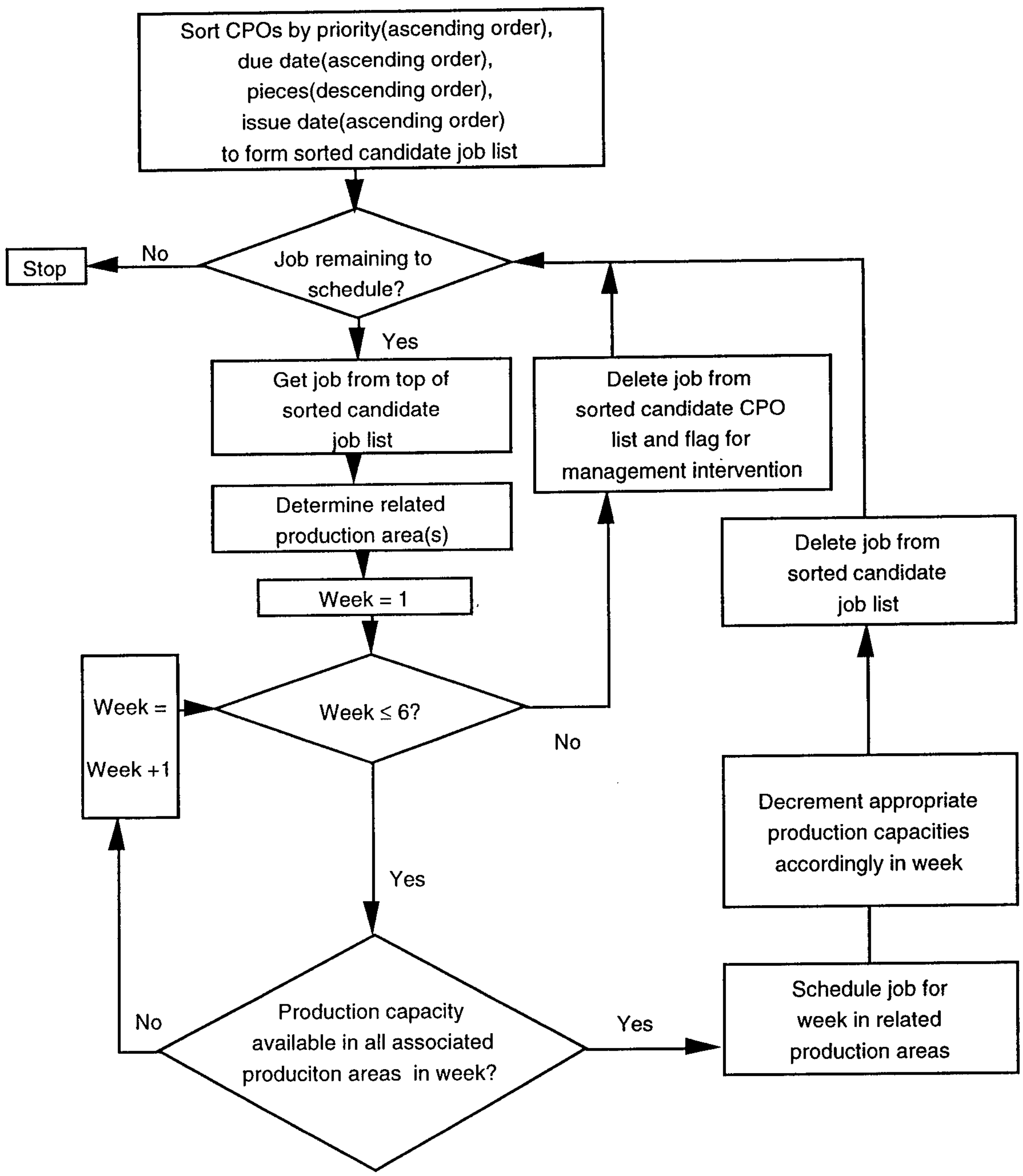

Figure 2. A simple sorting procedure serves as the basis for the scheduling heuristic.

We designed both the mixed integer and heuristic models to operate over a six-week rolling time horizon with weekly time periods. Scheduling results are implemented only during the first week of the short-term planning horizon. At the end of each week, parameters are updated and the given model is re-solved for the next planning period.

We evaluated the performance of the scheduling heuristic based on five sets of facility data. In each case, we solved the MIP using a linear optimizer on a personal computer platform. We compared the corresponding heuristic schedule with the results of the MIP multi-objective approach in which we varied the set of weights representing the relative importance of shortfall and inventory objectives to generate a set of nondominated solutions. From this set, management could then choose a preferred schedule. In all five cases, the heuristic performed well, yielding nondominated solutions close to management's preferred nondominated schedule. (In each case the MIP was employed to verify that the heuristic solution was a nondominated solution.) Figure 3 shows the relationship between the inventory and shortfall cost components for the heuristic solution and the set of nondominated solutions for one of the five test problems.

The introduction of this scheduling system has led to both tangible and intangible benefits at Tanner Companies. In a one year period amidst increasing demand, system implementation led to a $200,000 reduction in WIP, which in turn increased on-time deliveries from 74 percent to over 90 percent.

Daily Scheduling Subproblem

The daily scheduling subproblem, the third level model, is used to determine the best job sequence for one week of production as called for by the short-term planning model. The daily scheduling of garments through sewing operations is a multi-project scheduling problem where a *project* is defined as a sequence of operations that must be performed according to a set of precedence requirements. In apparel, the construction of any garment requires processing through a set of sewing operations that must be completed in a specific order. Each operation requires a fixed sewing and processing time using a set of limited resources such as sewing equipment and operators. Once started, an operation such as "set sleeve," continues until completion. Projects are scheduled through the assignment of start and finish times for each operation within these precedence, equipment, and labor constraints to minimize garment completion times. The daily apparel scheduling problem is deemed "multi-project" since a number of different garment styles are produced concurrently in a given sewing department and must simultaneously share limited resources within the constraints imposed by the individual precedence requirements.

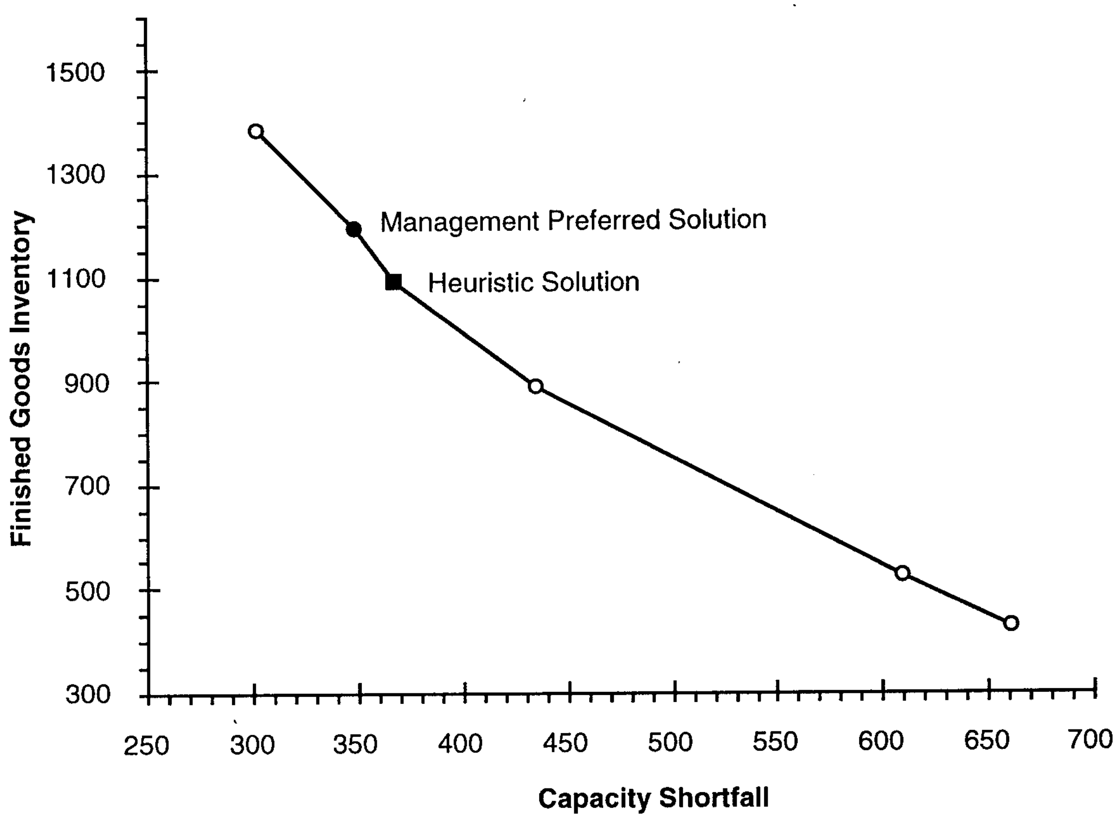

Figure 3. Relationship between inventory and shortfall components for the heuristic solution, the set of nondominated schedules generated by the MIP model (open circles), and the management preferred nondominated MIP solution. Note that the inventory and shortfall cost units used to generate this figure are not commensurate.

A linear programming formulation of the multi-project scheduling problem appears in the appendix. The formulation minimizes unmet garment demand subject to garment demand, sewing capacities, and precedence relationships. Again, the size and nature of project/multi-project scheduling problem precludes obtaining the optimal solution via readily available computing equipment. Thus, solution efforts were focused on heuristic procedures aimed at the construction of good, although not necessarily optimal, solutions.

At Tanner, the scheduling heuristic was based on a priority dispatching rule methodology commonly used to schedule in a single project environment. In contrast to the multi-project scheduling problem, single project scheduling does not require the allocation of resources among competing projects but is simplified to resource allocation among operations of a single project. Priority dispatching rules are used to assign an ordinal priority to each operation. When a limited resource becomes free, the available operation with highest priority is chosen for processing subject to precedence constraints. Examples of commonly used priority dispatching rules are *first-come first-served* (FCFS), *shortest processing time first* (SPT), *earliest due date* (EDD), and *most work remaining* (MWKR).

To treat the daily planning problem as a multi-project scheduling problem, individual projects must be recognized from two distinct viewpoints: both as product types or styles and as smaller batches or bundles. Resources must be allocated at both the style and bundle level. Different garment styles represent completely different projects with different precedence and resource constraints. In contrast, bundles within a particular style represent different projects, with each project sharing identical resource requirements and precedence constraints.

The straightforward application of a priority dispatching rule to all bundles from a number of projects is not desirable for scheduling in the apparel industry. In SPT for example, all bundles associated with the style having the shortest schedulable operation would be assigned to all available worker and machine combinations. More realistically, a given operator would perform a specific sewing operation on only one or two bundles and such an assignment would lead to significant declines in productivity. Because a number of styles and fabrics flow through a given department in a single day, there is an element of learning involved each time a new operation is encountered. A minimal level of repetition (consecutive identical bundles) is desirable to ensure high enough sewing efficiency. There are also other complications. Following completion of a given operation on a particular style, all available worker and machines would proceed to sew the bundles from the particular style with the next shortest schedulable operation. The style may or may not require the same machine setup (thread color, button color and type, cam, etc.) as the preceding style. Thus, priority dispatching could lead to significant setup changes for subsequent bundles.

To avoid such problems, available resources are first assigned among different styles based on product due date and total remaining processing time. For example, a style requiring 160 total processing hours would use an average of four employees to ensure completion during a forty hour work week. Thus, four worker resources would be allocated to such a style for the week. The same four employees would not necessarily work on this style at all times, but on average, four employees and four pieces of sewing equipment would be processing this particular style throughout the week. Following worker allocation, an appropriate priority dispatching rule is applied to each style based on the required precedence relationships.

At Tanner, the heuristic was applied over a period of one week in the jackets department. At the time of application, the jackets department employed 31 full-time sewing operators. The department had 43 machines, consisting of 26 generic sewing machines and 17 specialized machines (Table 1). To illustrate the complexity of the sewing operations required for the construction of a ladies jacket, a typical set of precedence constraints is presented in Figure 4. The garment involves 56 operations and requires 5 different resource types. (The circled numbers in Figure 4 correspond to jacket sewing operations and the arrows indicate the precedence of these operations.) A complete description of the algorithm is given in the appendix.

Table 1. Resource Availability in Jackets Department

Resource Type	Number of Machines
1	26
2	4
3	5
4	1
5	1
6	1
7	1
8	1
9	1
10	2

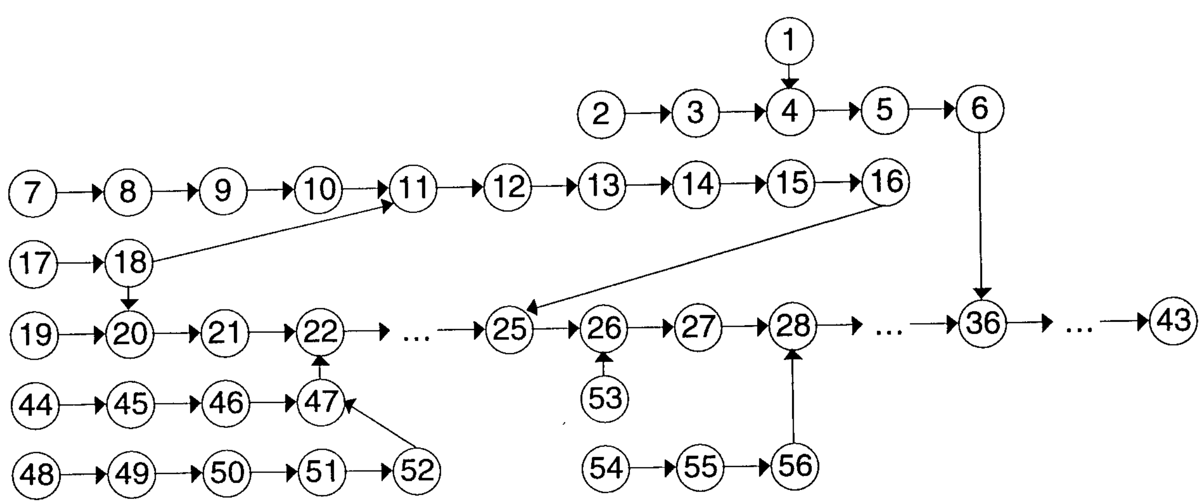

Figure 4. Typical Set of Precedence Constraints for Construction of a Ladies' Jacket.

Following worker allocation to garment styles, bundles were sequenced through operations using a priority dispatching rule. The choice of priority dispatching rules was based on an analysis of jacket precedence diagrams as depicted in Figure 4. In all cases, the tree-like diagram was characterized by a number of dependent operations arranged sequentially to form a lengthy "trunk" that continued to the project termination point. To progress rapidly to the trunk, the scheduling heuristic was based on the "most work remaining" (MWKR) priority dispatching rule [1] in which priority is given to the operation with the most remaining work to follow. A description of the scheduling heuristic is given in the appendix.

Before allocation, resource categories were classified into two groups: personnel and equipment. The decisions regarding the allocation of personnel were removed from the problem through the initial apportionment of workers to garment styles. Thus, no further allocation of the workers was required between different garments as scheduling proceeded. However, when bundles competed for equipment, they were distributed as described previously using the priority dispatching rule that assigns priority to the bundle with the "most remaining work." Ties in priority were resolved in favor of the bundle operation with the earliest due date.

This model was used to schedule Tanner's jackets department for a one week period based on historical data. During the particular week studied, 15 styles (178 bundles) were available for scheduling. The number of operations per style ranged from 21 to 60, with an average of 49 operations per style. Ten of the fifteen styles were in process at the beginning of the week. The remaining five had not been started.

The heuristic resulted in significant improvements during the one-week period studied. The model schedule led to a 5.1% increase in productivity over the actual schedule. In addition, the model resulted in the completion of two more styles than the actual schedule. However, due to an inability to collect real-time production data at Tanner, this scheduling model has only been tested using historical data.

SUMMARY

The hierarchical planning system provides a comprehensive approach to an extremely complex production planning and scheduling problem. The model provides a formal link between long-term and short-term planning. The three-tiered hierarchical model includes long-term inventory planning, shorter-term production planning, and daily operations sequencing. The subproblems are linked in that decisions developed in the longer time horizon models impose operational constraints on the shorter term models. In turn, actual production and orders are periodically updated and each model reapplied so that the production decisions reflect the most current information.

All components of the three-tiered model were tested at Tanner Companies, Inc. The results from the long-term inventory planning model looked promising but could not be compared quantitatively against historical data. For production planning, the model decisions increased on-time deliveries from 74% to 90+% and produced a $200,000 decrease in work-in-process inventories. Finally, the daily operations sequencing model produced a 5.1% increase in productivity.

Although the three models were tested individually, the overall integrated model could not be tested due to the inability to capture and process necessary data and information in a timely fashion. The second level short-term planning model has been implemented at Tanner. The installation and daily use of this model have led to significant measurable improvements in the reduction of WIP levels and increased on-time deliveries. While the significant benefit of each model in the three-tiered hierarchy has been demonstrated, even further improvements should result from a complete integration over a longer period time.

For future use, the proposed system presents an opportunity for significant progress in the area of *quick response* because of the model emphasis on efficiency and responsive to current demand and production environment. The success of the system depends in large part on the quality, availability, and timeliness of the underlying information requirements. Efficient processing and transmission of information within a company as well as communication between manufacturer, suppliers, and retailers are critical to the success of such models. While benefits of each model component have been proven, the potential advantages and improvements from a completely integrated hierarchical production planning and scheduling system would be even greater with better access to production and demand data. This access may depend upon successful implementation practices such as an industry-wide *electronic data interchange* (EDI) system [14].

Appendix

Long-term Planning Subproblem

Minimize:

$$\sum_{m}\sum_{j}\left(h_j I_{jm} + t_j O_{jm} + u_j S_{jm} + g_j X_{jm}\right) + \sum_{D}\sum_{m}\left(s^{+}_{Dm} + s^{-}_{Dm}\right) \tag{1}$$

Subject to:

$$\sum_{j} X_{jm} \le C_m, \quad \forall m \tag{2}$$

$$\sum_{j} O_{jm} \le T_m, \quad \forall m \tag{3}$$

$$\sum_{j} S_{jm} \le U_m, \quad \forall m \tag{4}$$

$$I_{j,m-1} + X_{jm} + O_{jm} + S_{jm} - I_{jm} - SS_{jm} \le D_{jm}, \quad \forall j, m \tag{5}$$

$$\sum_{j \in J_D} X_{jm} = L_{Dm}, \quad \forall D, m \tag{6}$$

$$L_{Dm} + s^{+}_{Dm} - s^{-}_{Dm} = L_{D,m+1}, \quad \forall D, m \tag{7}$$

$$I_{jm}, X_{jm}, O_{jm}, S_{jm}, s^{+}_{Dm}, s^{-}_{Dm} \geq 0 \tag{8}$$

Decision variables:

X_{jm} = product j (or aggregate) production via regular time in month m;

I_{jm} = ending inventory for product j (or aggregate) in month m;

O_{jm} = product j (or aggregate) production via overtime in month m;

S_{jm} = amount product j (or aggregate) subcontracted in month m;

L_{Dm} = regular time capacity allocated to type/division D in month m;

s^{+}_{Dm} = excess production of type/division D in month m+1 over month m;

s^{-}_{Dm} = excess production of type/division D in month m over month m+1;

Parameters:

SS_{jm} = safety stock for product j in month m (if applicable);

D_{jm} = forecasted demand for product j in month m;

C_m = regular time production capacity in month m;

T_m = overtime production capacity in month m;

U_m = subcontracting capacity in month m;

h_j = holding cost for product j;

t_j = unit overtime production cost for product j;

g_j = unit regular time production cost for product j;

u_j = unit subcontracting cost for product j;

J_D = set of all products of type/division D.

The objective function (1) serves to minimize finished goods holding costs, overtime, subcontracting, and regular production costs as well as attain a balanced plant layout. Regular, overtime, and subcontracting capacities are reflected in constraints (2), (3), and (4) respectively. Constraint (5) ensures that product demand is satisfied while constraints (6) and (7) are necessary for balanced plant layout and loading. The decision variables include monthly ending inventory levels and production quantities for specified products. Note that product j may refer to either a forecasted or ordered end item j in the case of a basic apparel manufacturer. Product j may refer to either a first stock-run, a forecast reorder, or an ordered end item j in the case of a style shop. This model can be extended to a third type of apparel manufacturer, a combination style shop and basic manufacturer. In such a case, product j may refer to any combination of the product types described above.

Short-term Planning Subproblem

Minimize:

$$\sum_i \sum_k c_{ik}^u u_{ik} + \sum_{n \in N_m} \sum_j c_{nj}^m m_{nj} + \sum_{n \in N_l} \sum_j c_{nj}^l l_{nj} + \sum_n \sum_j \left(s_{nj}^+ + s_{nj}^-\right) + \sum_m \sum_j \left(s_{mj}^+ + s_{mj}^-\right) \quad (1)$$

Subject to:

$$\sum_{j=1}^{k} a_{ik} x_{ijk} + u_{ik} = d_{ik}, \quad \forall i, k \quad (2)$$

$$\sum_{i \in M_n} \sum_{k=j}^{w} a_{ik} x_{ijk} + m_{nj} = C_{nj}^m, \quad \forall j, \forall n \in N_m \quad (3)$$

$$\sum_{i \in L_n} \sum_{k=j}^{w} a_{ik} x_{ijk} + l_{nj} = C_{nj}^l, \quad \forall j, \forall n \in N_l \quad (4)$$

$$\sum_{j=1}^{k} x_{ijk} \le 1, \quad \forall i, k \quad (5)$$

$$l_{nj} + s_{nj}^{l+} - s_{nj}^{l-} = l_{n+1,j}, \quad \forall j, n \quad (6)$$

$$m_{nj} + s_{nj}^{m+} - s_{nj}^{m-} = m_{n+1,j}, \quad \forall j, n \quad (7)$$

$$x_{ijk} \in \{0, 1\}, \quad \forall i, j, k \quad (8)$$

$$u_{ik}, m_{nj}, l_{nj}, s_{nj}^{l+}, s_{nj}^{l-}, s_{nj}^{m+}, s_{nj}^{m-}, \ge 0 \,. \quad (9)$$

Decision variables:

u_{ik} = underage of product i in week k;

m_{nj} = underage or production shortfall for modular n in week j;

l_{nj} = underage or production shortfall for production line n in week j;

x_{ijk} = 1 if product i produced in week j for demand in week k; 0, otherwise;

s_{nj}^{l+} = excess underage for line n+1 over underage for line n in week j;

s_{nj}^{l-} = excess underage for line n over underage for line n+1 in week j;

s_{nj}^{m+} = excess underage modular n+1 over underage modular n in week j;

s_{nj}^{m-} = excess underage modular n over underage modular n+1 in week j.

Parameters:

c_{ik}^{u} = cost of underage product i demand week k;

c_{nj}^{m} = cost of underage modular n production week j;

c_{nj}^{l} = cost of underage line n production week j;

a_{ik} = amount of product i demanded in week k;

d_{ik} = demand for product i week k;

w = number of periods in level two horizon;

M_n = set of products produced in modular n;

C_{nj}^{m} = capacity of modular n week j;

C_{nj}^{l} = capacity of production line n week j;

L_n = set of products produced on production line n;

N_m = set of all modular production units;

N_l = set of all regular production lines.

The objective function (1) serves to minimize unmet demand and production shortfall or underage cost, as well as balance the production load among manufacturing lines and modular units. Constraint (2) requires product demand be met while constraints (3) and (4) reflect modular and line capacities respectively. A given product is scheduled for production at most once in the short-term time horizon as reflected in constraint (5). Constraints (6) and (7) are necessary for load balancing. Decision variables include indicators for the manufacture of all products by week as well as underages for demand and production capacities. Additional capacity constraints similar to constraint sets (3) and (4) may be added as necessary to accurately model particular production facilities.

Several minor changes were made to this model to accurately reflect the production environment at Tanner. First, the objective function was reduced to minimizing capacity underages on production lines and modular units while at the same time minimizing inventory holding costs to avoid unnecessary finished goods inventories. Weights were assigned to represent the relative importance or appropriate tradeoff between these two goals. Constraint (5) was changed to an equality. Constraints (2), (6), and (7) were not necessary at Tanner. Additional constraints related to cutting requirements were added.

Daily Scheduling Subproblem

Minimize:

$$\sum_i u_i \tag{1}$$

Subject to:

$$\sum_i x_{ijt} \le c_{jt}, \quad \forall j, t \tag{2}$$

$$\sum_{k=1}^{t-1} x_{ijk} - \sum_{k=1}^{t-1} x_{i,j+1,k} \ge x_{i,j+1,t}, \quad \forall i, j, t \tag{3}$$

$$\sum_k x_{iLk} + u_i = d_i, \quad \forall i \,. \tag{4}$$

Decision variables:

x_{ijt} = amount of product i processed for operation j at time t,

u_i = unmet demand for product i.

Parameters:

c_{jt} = capacity of operation j at time t,

d_i = demand for product i.

The objective function (1) serves to minimize unmet demand as specified by the second level short-term planning model. Capacities on daily operations are reflected in constraint (2). Constraint (3) represents the precedence of operations for all products while constraint (4) describes product demand. The decision variables include unmet demand quantities and the amount of a particular product processed daily at a given operation.

Worker Assignment Algorithm

1. Define:

   M = number of styles to be scheduled during the week;

   S_i = total number of sewing hours remaining to complete style i;

   W_i = week style i is due where 1 denotes current week;

   R = initial number of workers available in current production week;

   V = number of workers available as assignments are made;

   E_i = number of workers to be assigned to style i in week 1 to complete style i in week i as computed below in step 3.

2. Sort styles on due date in ascending order.
3. For each week i = 1 to M, do the following:

   Calculate E_i = integer part of $(S_i / (40 \times W_i))$;

   If $(E_i \leq V)$ then

      Assign E_i workers to style i and update V to $V - E_i$;

   Else If $(V > 0)$

      Assign V workers to style i and set V to zero.

4. While $(V > 0)$

      For each week i = 1 to M, do the following:

         Assign an additional half worker to style i and decrease V by a half.

5. Stop.

Scheduling Algorithm

1. Define:

   p_{ijk} = processing time for style i, bundle j, operation k;

   C = number of time periods available in current week;

   c = current time period.

2. Set c = 0.

3. Assign label $a_{ijk} = p_{ijk}$ for all style/bundle/operations with no successors.

4. For all remaining style/bundle/operations, assign the label $a_{ijk} = p_{ijk} + a_{ijl}$ when operation l is the immediate successor of operation k, style i, bundle j.

5. Sort all style/bundle/operations based on label as the primary key in descending order and due date as the secondary key in ascending order.

While operations remain to be scheduled, do the following:

6. Set c=c+1, n=0;

   If c>C, stop.

7. Set n = n+1.

8. If all immediate predecessors to n^{th} operation on sorted list have been scheduled and both equipment and worker resources are available for n^{th} operation listed in period c, then:

   Schedule nth operation listed to start in period c;

   Remove n^{th} operation from list.

9. If all operations have been considered for scheduling in period c,

   Go to step 6;

   Else go to step 7.

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